MARS AND THE SEARCH FOR LIFE ELSEWHERE: INNOVATIONS IN THE THIRD ERA OF SPACE EXPLORATION

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Abstract

It has been thirty-six years since the Mariner 2 flyby of Venus opened the first era of space exploration, during which the main technical challenge was "getting there." This led to the second era in which the technical and scientific challenge was the development and operation of large, comprehensive observational systems to find what was out there. We are now in the third era of space exploration, with the engineering and scientific challenges of getting there often for in-situ exploration and of returning samples to Earth. One of the principal scientific objectives of the third era is the search for life elsewhere.

The First Era

In the first era, just getting there was the main driver of innovation. Mariner 2 (Figure 1) flew by Venus on December 14, 1962. Although communication was lost about two weeks later, Mariner 2 measured surface temperatures of 800-900 °F and made the first observations of the supersonic solar wind during its interplanetary cruise.

The next challenge was Mariner 4 (Figure 2), which reached Mars in 1964. Innovation was driven by the challenge of both getting there and returning the first digital images from deep space (bottom of Figure 2). The data rate was 8-1/3 bits per second, and the less than 1% of the surface that was imaged appeared to differ little from the Moon with its heavily cratered surface.

The Second Era

The first era of the NASA exploration program lasted about a decade and set the stage for the next era in which the engineering and scientific challenges were in finding what was out there. Because so little was known, a wide range of measurements were needed, requiring the development of autonomous survey spacecraft involving the integration and control of many complex sensors. As a result, these were large spacecraft. Voyager had a mass of 800 kg, and Viking was 3500 kg; Cassini with a launch mass of 6000 kg was the most complex planetary spacecraft ever launched. Innovations emphasized autonomy, system integration, and mission design.

The Viking mission placed two landers on Mars in 1976, searching for life on the cold, dry surface. Voyager flew by Jupiter, Saturn, Uranus, and Neptune, revealing the complexity and diversity of the outer solar system. Galileo, in orbit around Jupiter since December 1995, dropped a probe into the atmosphere of Jupiter and is now flying within a few hundred kilometers of the moons of Jupiter. The culmination of this sequence of spacecraft is Cassini, launched on its way to Saturn in October 1997.

The cost of these missions (about $1-2 billion each) meant that only one was launched each decade: Galileo returned to Jupiter 16 years after Voyager was there; Cassini will return to Saturn 23 years after Voyager was there. Such a pace is acceptable for global surveys, but not for in-situ exploration that requires returning often so as to study the wide geological and environmental diversity of other worlds. However, to afford going much more often, the cost for each mission must be correspondingly less.

The Third Era

In the third era of space exploration, innovations are driven by getting there often, landing on and penetrating the surface, and returning samples to Earth. The challenge is reducing the cost and mass of each spacecraft by a factor of 10 or 20, while introducing new scientific capability and broadening public engagement. The shift away from one large mission per decade to a series of much lower cost missions has been accompanied by a shift away from individual projects, which had their own funds to develop project-specific technologies, to sets of linked projects known as programs. Among these are the Mars Surveyor Program, a series of missions to explore and return samples from the Martian surface, the Outer Planets/Solar Probe Program of missions to Europa, Pluto, and the Sun, and the Origins Program that includes the astronomical search for planets around other stars.

In the third era, individual projects are completed on such a short timescale and with such limited funds that there is no time to develop project-specific technology. As a result, technology must be developed outside of individual projects through a set of linked technology programs: Exploration Technology Program; Origins Technology Program; and Deep Space Systems Technology Program.

Flight demonstrations of innovative technologies are also key to the third era. The New Millennium Program is intended to demonstrate a wide range of technologies for the Origins, Outer Planets, and Mars Programs.

This new structure for space exploration — sets of linked missions comprising programs that are in turn linked to technology programs — allow more frequent and lower cost missions that will facilitate in-situ exploration, sample return, and the search for life elsewhere.

Mars

In many ways, Mars (Figure 3) is the planet most closely resembling Earth, and twenty-five years ago many attributes of Mars suggested the possibility of past or present life. In 1977, two Viking landers searched for but found no evidence of life on the Martian surface. Just a year later, life was discovered proliferating in darkness around thermal vents on the Earth's ocean floor. Instead of relying on sunlight, these ecosystems depend on chemical energy boiling up from the Earth's interior. Life has also been found at freezing temperatures underneath and within Antarctic sea ice and in rock from several miles below the surface in Washington State.

Life is more robust than imagined twenty-five years ago, thriving in extreme environments wherever there is liquid water and a source of energy. Many of these extremophiles are a new form of life called *Archaea* — independent of, but sharing a common ancestor with previously known forms of life.

There is also evidence that life evolved more rapidly on Earth than previously thought. Ancient microfossils in Western Australian rocks that are three-and-a-half billion years old indicate that life evolved very rapidly, likely appearing on Earth nearly four billion years ago.

Common to these observations of life is the presence of water, and there was a lot of water on Mars at one time. Wide channels (Figure 4) that are much broader than any on Earth, were carved by massive, episodic floods. Other areas (Figure 5), appear to be dry lake beds. These and other features suggest bodies of standing water on Mars three-and-a-half billion years ago and episodic floods within the last several billion years. So there was time for life to evolve before liquid water disappeared from the surface. Thus, a first step in searching for evidence of life is to look for where there was water. This is the underlying strategy for exploring Mars. Every twenty-six months there is an opportunity to go to Mars, and the first two missions of the third era were launched in late 1996.

Mars Global Surveyor was launched in November 1996 and arrived in September 1997, entering a polar orbit from which it will systematically map and examine the composition of the surface of Mars. Investigators will search for regions on Mars where there was thermal activity at one time, similar to Yellowstone National Park on Earth. Currently, no active thermal spots are known, but there may be chemical signatures of past thermal regions. Using the spacecraft camera to image surface features only five feet across, it will be possible to examine areas where there was water, and therefore where life might have evolved. Although Mars Global Surveyor will not reach its final mapping orbit until March 1999, early results show what appears to be a dry stream bed (Figure 6) and a North Polar ice cap (Figure 7) that is too small to contain more than 10% of the water thought to have been present on the surface at one time.

Mars Pathfinder was launched in December 1996, traveling directly to Mars and landing on July 4, 1997. Surrounded by air bags, the lander dropped to the surface carrying the small rover, "Sojourner." About a foot tall, weighing twenty-five pounds, and running on an average power of eight watts, Sojourner carried an alpha-proton x-ray spectrometer for determining the composition of various rocks. Sojourner found them to be silicon rich, indicating a more complex geological history than previously thought.

The Mars Climate Orbiter, launched in December 1998, will observe the global distribution of water vapor in the atmosphere, while the Japanese Nozomi spacecraft will study other aspects of the Martian atmosphere. The Mars Polar Lander, launched in January 1999, will land near the South Pole of Mars where a polar cap of frozen carbon dioxide (dry ice) grows and shrinks with the seasons. At this landing site, which is within fifteen degrees of the pole, the layered terrain is built up of wind-blown deposits from many annual cycles.

This Mars mission is the next step in searching for the most likely spots where water once existed on Mars — and perhaps where it exists today as ice. A small stationary lander (Figure 8) will use a robotic arm to scoop up soil samples that will be heated so that volatiles such as water can be measured. Two small microprobes released by Mars Polar Lander as it approaches Mars will penetrate up to three feet beneath the surface, analyzing the soil for ice.

The NASA plan for future Mars exploration (Figure 9) combines a series of orbiting and landing spacecraft. The orbiters will map the surface and analyze the atmosphere, allowing the identification and evaluation of the most interesting spots to land and explore. In 2001, an orbiter and lander will head toward Mars, and in 2003, the first sample-collecting rover will land. It will analyze rocks and take samples of the most interesting ones. Using a small Mars Ascent Vehicle, the cache of samples will be launched into Mars orbit, waiting for retrieval. The ESA Mars Express Orbiter is also planned for launch in 2003.

In 2005, another lander and rover will be sent to retrieve samples from another site. A separate sample return spacecraft, possibly built by the French Space Agency, will rendezvous with the rock caches orbiting Mars, returning them to Earth in 2008 for detailed analysis .

Europa and the Outer Planets

While Mars is an exciting place to search for life elsewhere, it is not the only place. On Earth, life began in the oceans and persists today without need for sunlight. Europa, a moon of Jupiter, may also have an ocean. About the size of Earth's Moon, its icy crust is the smoothest in the Solar System (Figure 10), with no mountains or valleys and few impact craters. Narrow white ridges, about 500 ft high, are accompanied by somewhat darker deposits (Figure 11, false color) that suggest the ridges may have formed by eruptions from below the ice. Geologically, such eruptions are fairly recent because the paucity of impact craters indicates a young surface, although it is unknown if eruptions are still occurring. There are other features resembling an ice pack (Figure 12) that also suggest that there was liquid water at one time. A key question is whether liquid water is present today beneath the icy crust. As the Galileo spacecraft continues to orbit Jupiter it may provide further evidence for the possibility of a liquid water ocean under Europa's icy crust.

The next step in the exploration of Europa is to determine the thickness of the rigid crust by laser altimetry and radar sounding. To do so requires orbiting Europa rather than Jupiter. The first mission planned for NASA's Outer Planets/Solar Probe Program is the 2003 launch of a 385-kilogram spacecraft (dry mass) carrying a radar sounder, an imager, and a laser altimeter.

Subsequent missions using the same spacecraft technology include a 200-kilogram spacecraft to Pluto and the Kuiper Belt, and a Solar Probe spacecraft that will use the gravity assist of a Jovian flyby to return to within 3 solar radii of the solar surface.

A linked technology program called X2000 is developing the innovative spacecraft technologies needed to decrease the Outer Planets/Solar Probe spacecraft mass and cost. The approach is to reduce spacecraft avionics to a set of boards and eventually to a chip set that requires much less power while providing much greater computing power. Another challenge for the X2000 program is the Europa radiation dose of 4 megarads.

Titan

The Solar System holds other places of biological interest. Saturn's moon Titan (Figure 13) is especially interesting. Almost as large as the planet Mercury, Titan has a substantial atmosphere with a surface pressure 60 percent greater than on Earth. Titan's atmosphere, like Earth's, is 80 percent nitrogen, but unlike Earth, it has significant methane and no oxygen. On Titan, sunlight creates a smog of organic compounds, forming an opaque haze that blocks a view of the surface. The organic chemistry occurring there today may, in some ways, resemble that which occurred in the Earth's early atmosphere before life evolved.

The NASA/ESA Cassini/Huygens Mission will arrive at Saturn in 2004. As the spacecraft orbits Saturn, it will fly by Titan, imaging the surface beneath the opaque haze with a radar system developed jointly with the Italian Space Agency. The spacecraft also carries the ESA Huygens atmospheric probe (Figure 14) that will carry a set of instruments to analyze the organic chemistry in Titan's atmosphere.

Titan may hold important clues to the origin of life in the Solar System. Just as the Earth's polar caps retain layer upon layer of frozen evidence of past climate, the surface of Titan may have layer upon layer of frozen organic compounds from past eons of atmospheric chemistry.

Comets

Comets are also of interest because they may have had a role in the origin of life. The abundant water ice in the outer Solar System as it formed resulted in comet-like objects, some of which collided and coalesced to form the cores of the giant planets. Others were scattered outward to form the Oort Cloud, from which a few occasionally return as comets.

Although comets are mainly water ice, their surfaces are charcoal black. When the ESA Giotto spacecraft flew by Comet Halley in 1986 (Figure 15), it analyzed the atomic constituents of the material coming off the surface, finding hydrogen, nitrogen, oxygen, and carbon — the building blocks of organic molecules. Where did this black material come from? Was it part of the interstellar matter out of which the Solar System formed? What role did this black material have in seeding the inventory of organic compounds that were in the Earth's ancient oceans, and perhaps on other planets, before life evolved? Answering these questions requires analysis of the molecular constituents of a sample of the black material.

One way to obtain a sample is to fly through a comet's coma. Because the flight through the coma is so rapid, any material captured on a solid surface would evaporate on impact. To collect the comet dust, a material called aerogel (Figure 16) will be used. This silica material is so porous that its density is only eight times that of air. Even at a flyby speed of 6 km/s (13,000 mph), the tiny dust particles will be captured intact in the aerogel for return to Earth.

The Stardust spacecraft will be launched in February 1999 for an encounter with Comet Wild II in January 2004. Analysis of the organic constituents of the sample returned to Earth in January 2006 should provide important clues about the origin of the material and the contribution comets may have made to the inventory of organic compounds in the oceans before life evolved.

Life Around Other Stars: The Origins Program

The search for life also extends beyond the Solar System. An image from the Hubble Space Telescope (Figure 17) shows clouds of dust and gas up to a light year in extent. These are the stellar nurseries of the Eagle Nebula, where stars and their planetary systems are born by the collapse of dust and gas within the cloud and are revealed as the surface of the cloud around them evaporates from the intense radiation of nearby bright stars.

Newly formed stars are often surrounded by a disk of residual dust that radiates heat in the infrared. The Infrared Astronomy Satellite produced evidence of such a disk around Beta Pictoris in 1983. An infrared image obtained by the Keck telescope of another nearby star (Figure 18) shows a disk that is about 200 astronomical units (AU) in diameter, about twice that of the solar system. The distribution of infrared light shows evidence of a 100-AU diameter hole in the middle of the disk that likely formed as the dust coalesced into planets.

The search for nearby stars with disks of dust is one of the objectives of the Space Infrared Telescope Facility, an 85-centimeter telescope operating at liquid helium temperatures and scheduled to be launched in December of 2001 with a five-year mission lifetime. The challenge is to find not only more of these disks, but the planets themselves.

The search for other planetary systems is part of the Origins Program, which anticipates the sequence of developments shown in Figure 19. The two Keck 10-meter telescopes will be connected together as an interferometer, so that the two giant telescopes separated by 85 meters act as if they are part of a much larger telescope that is 85 meters (280 feet) in diameter. The resulting angular resolution will allow the detection of Uranus-sized planets by the wobble they induce in the star about which they orbit.

The next step in the search for planets around other stars requires an interferometer in space. Two different approaches are being pursued. The Deep Space 3 mission to be launched in 2003 would include two free-flying spacecraft with small mirrors. The technology challenge is making the two mirrors behave as though they are part of a much larger mirror by formation flying: maintaining their separation to within a centimeter, their alignment to a few tenths of a milliradian, and optical calibration or metrology to a few nanometers. The Deep Space 3 mission will help evaluate the feasibility and affordability of using free flying spacecraft for interferometry.

A second approach will be taken in 2005: the Space Interferometer Mission. This mission would do astrometry, looking at the wobble of planets induced by orbital motion. This system, with a 10-meter baseline, would have an angular resolution of one microarcsecond or 5 picoradians, corresponding to 75 cm (30 inches) at the distance of the Sun. This would allow the detection of the wobble of any nearby stars that are orbited by Jupiter-like planets.

The direct detection of much smaller Earth-like planets requires the Planetfinder, a significantly larger interferometer that will allow a spectral analysis of the atmospheric composition of such planets. These observations should reveal the presence of atmospheric constituents associated with living organisms, such as oxygen and methane.

New Millennium Program

Linked technology programs provide the enabling innovations for today's missions. These new technologies are demonstrated in a series of missions known as the New Millennium Program, and Deep Space 1 is the first such NASA mission. Although it will fly by an asteroid and a comet, its principal focus is the flight demonstration of twelve technologies, including solar electric ion propulsion. Launched in October 1998, the 375-kilogram spacecraft carries 80 kilograms of xenon propellant. Although the thrust is very small, over a period of a year it will change the spacecraft velocity by 3 kilometers per second, providing the ability to navigate the spacecraft around the inner solar system under power. This will enable future spacecraft to rendezvous with a comet or asteroid, retrieve a sample, and then return to Earth.

The Deep Space 2 mission includes two small microprobes that will plunge into Mars on December 3, 1999. The two probes will bury themselves up to a meter in the soil near the South Pole, carrying small augers to pull in soil and small tunable diode laser sensors sensitive to any water vapor released from the soil as it is heated. Deep Space 2 is intended to demonstrate the technical feasibility of using such probes to establish a network of sensors on Mars. The technology for retrieving and returning a sample from the surface of a comet will be demonstrated by Deep Space 4/Champollion, a joint NASA/CNES mission that will use solar electric ion drive to match the spacecraft velocity with that of the comet.

Summary

The first two eras of space exploration have provided global surveys of dozens of moons and all the planets except Pluto, setting the stage for the current era of returning often for in-situ studies at diverse locations and bringing samples back for intensive analysis. Realizing the scientific opportunities of the third era requires innovations that significantly reduce the mass and cost of individual missions while extending their scientific capabilities for studies on and beneath the surfaces of other bodies. A vigorous, affordable program of in-situ exploration and sample return combined with the astronomical search for Earth-like planets around nearby stars will enable the search for life elsewhere in the solar system and beyond, a search that should lead to a better understanding of the origin of life on Earth.

Acknowledgment

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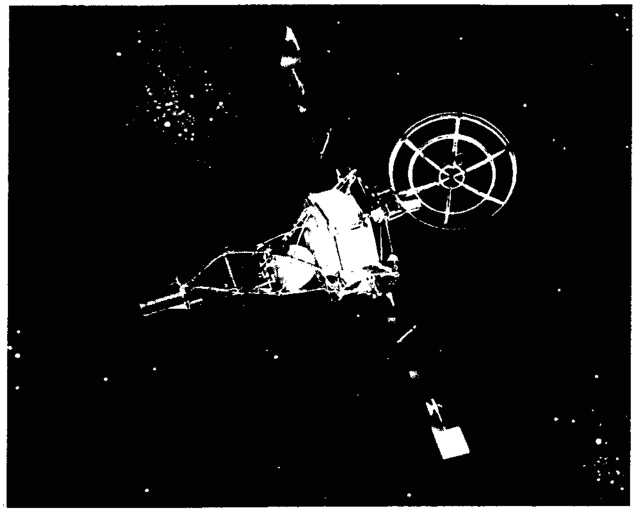

Fig. 1 Mariner 2

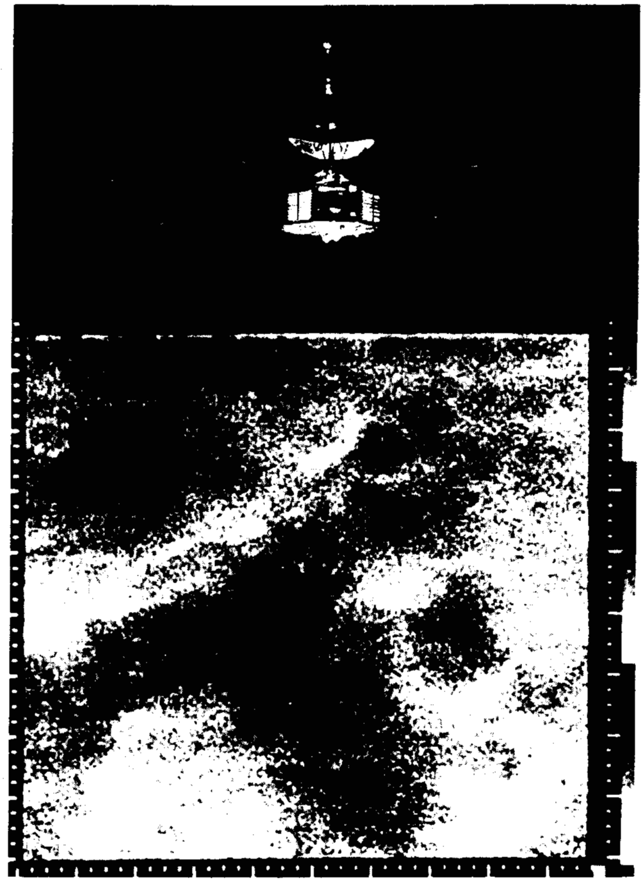

Fig. 2 Mariner 4

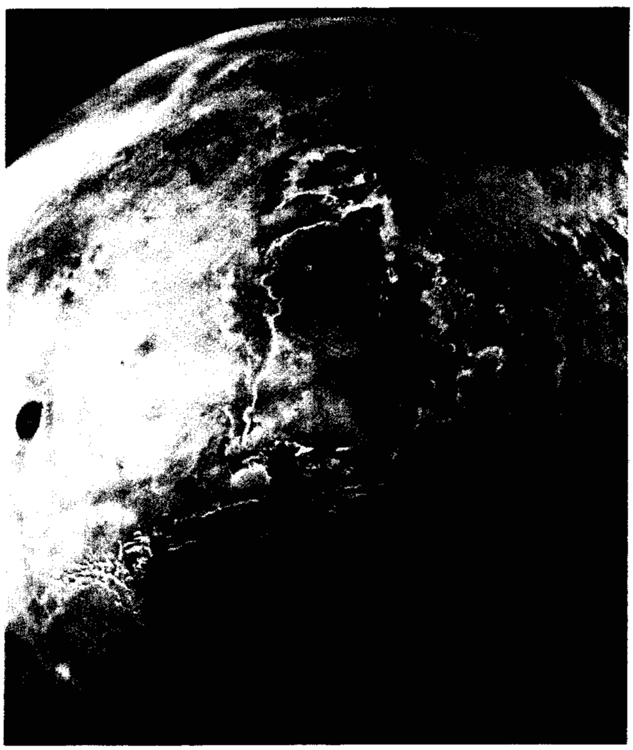

Fig. 3 Mars

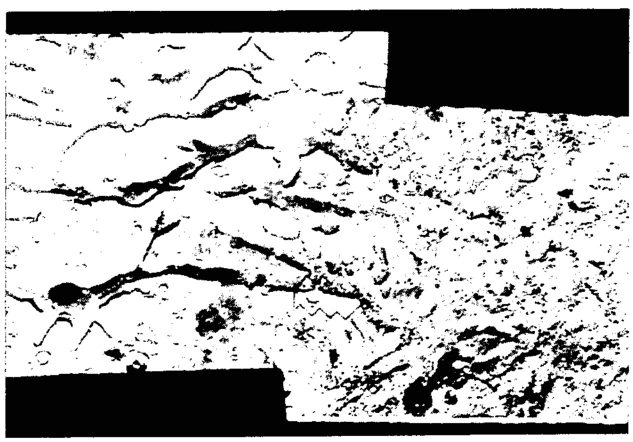

Fig. 4 Channels on Mars

Fig. 5 Lake Bed on Mars

Fig. 6 Canyon Wall of Nanedi Vallis

Fig. 7 Polar Ice Cap on Mars

Fig. 8 Mars Polar Lander

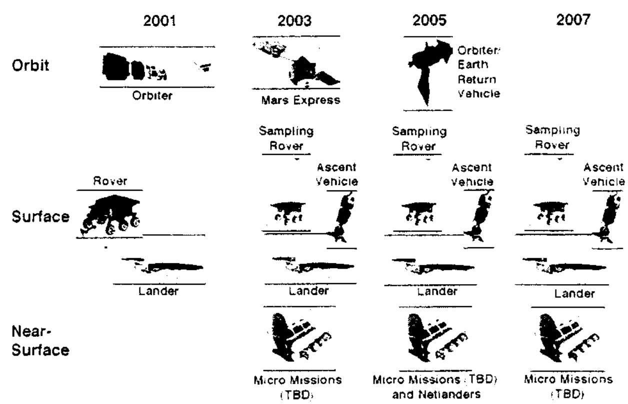

Fig. 9 Future Mars Missions

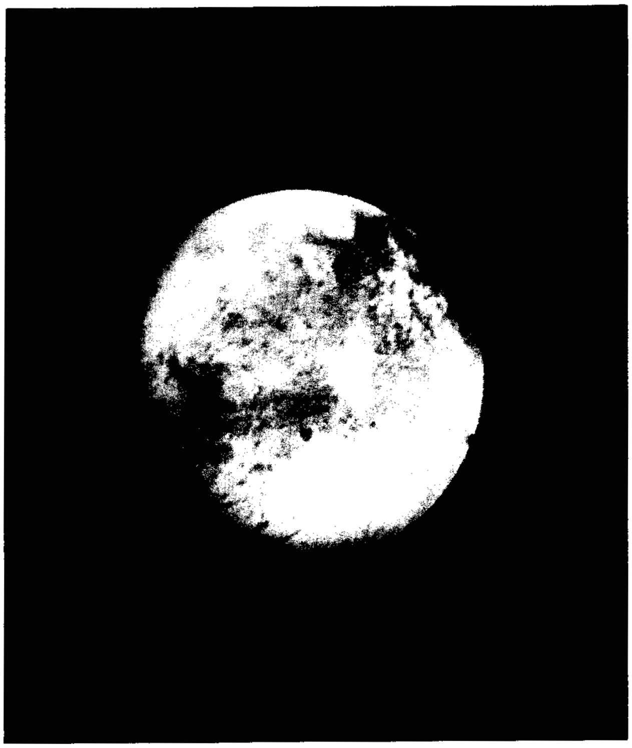

Fig. 10 Europa, a Moon of Jupiter

Fig. 11 Ridges on Europa

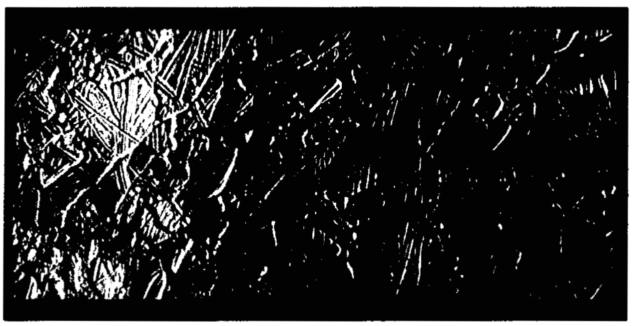

Fig. 12 Ice Pack on Europa

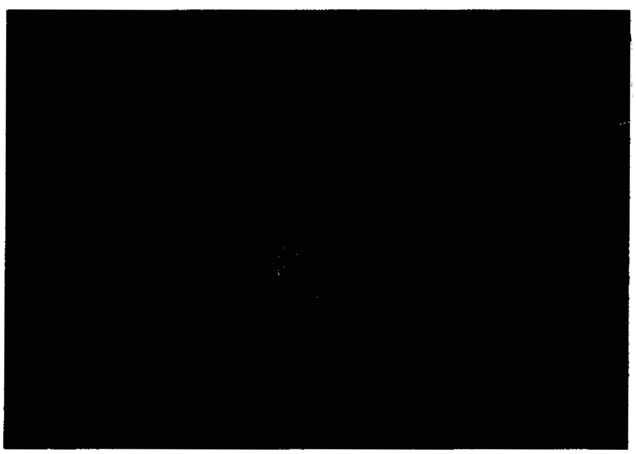

Fig. 13 Saturn's Moon Titan

Fig. 14 ESA-Huygens Atmospheric Probe

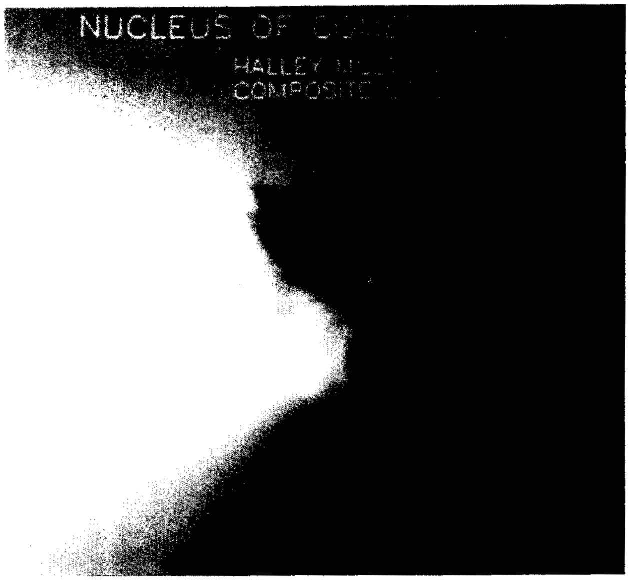

Fig. 15 Comet Halley

Fig. 16 Aerogel

Fig. 17 Image by Hubble Space Telescope

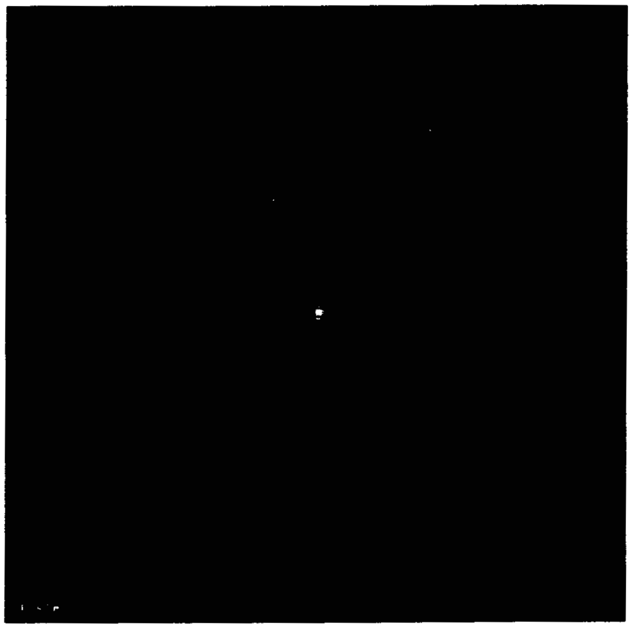

Fig. 18 HR4796 by Keck Telescope

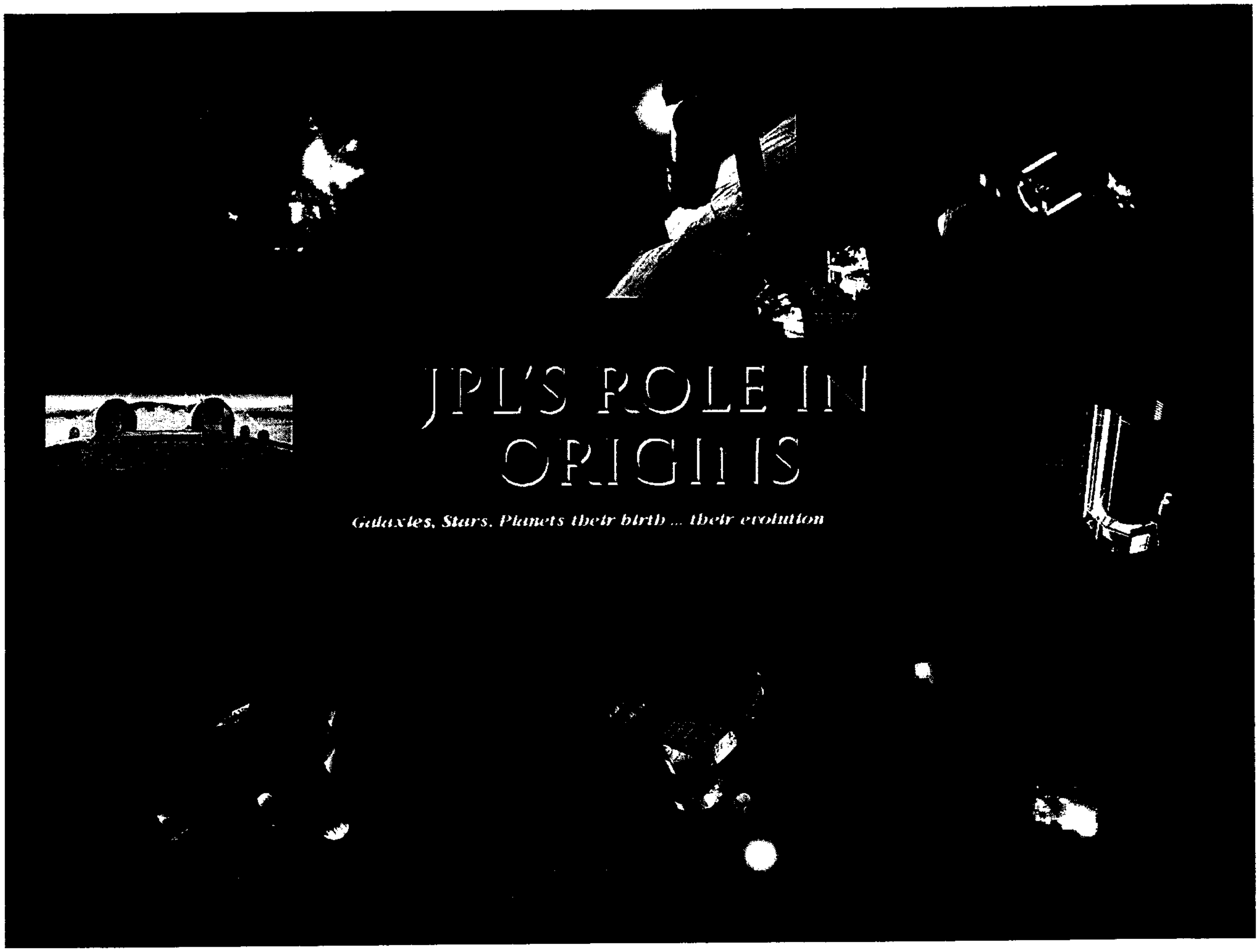

Fig. 19 Origins 2000